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Adapting prescribed burns to future climate change in Mediterranean landscapes

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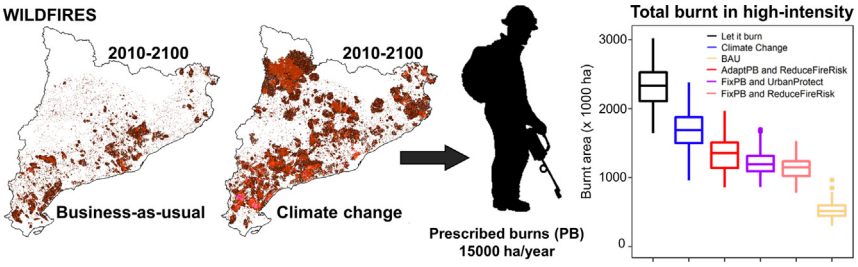
HIGHLIGHTS

- We assessed fire management effects on fire regime under climate change.
- Projected higher burnt area is partially offset by new suppression opportunities.
- Prescribed burning reduce high-intensity fires associated with climate change.
- Adaptive prescribed burning gain in cost-efficiency compared to rigid strategies.
- Relaxing fire suppression is a cheap option but leads to higher undesired impacts.

GRAPHICAL ABSTRACT



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ABSTRACT

Fire regimes are shifting or are expected to do so under global change. Current fire suppression is not able to control all wildfires, and its capability to do so might be compromised under harsher climate conditions. Alternative fire management strategies may allow to counteract predicted fire trends, but we lack quantitative tools to evaluate their potential effectiveness at the landscape scale. Here, we sought to quantify changes in fire regimes induced after the implementation of different fire management strategies. We developed and applied a new version of the model MEDFIRE in Catalonia (Mediterranean region of ~32,000 km^2 in NE Spain). We first projected burnt area from 2016 to 2100 resulting from climate change under the Representative Concentration Pathway 8.5 scenario of HadGEM-CC model and under current fire suppression levels. We then evaluated the impacts of four fire management strategies: 'Let it burn', fixed effort of prescribed burning with two different spatial allocations, and adaptive prescribed burning dynamically adjusting efforts according to recent past fires. Results predicted the emergence of novel climates associated with similar barometric configurations to current conditions but with higher temperatures (i.e. hot wind events). These novel climates led to an increase in burnt area, which was partially counteracted by negative fire-vegetation feedbacks. All prescribed burning scenarios decreased the amount of high-intensity fires and extreme fire events. The 'Let it burn' strategy, although less costly, was not able to reduce the extent of high-intensity fires. The adaptive prescribed burning scenario resulted in the most cost-efficient strategy. Our results provide quantitative evidence of fire management effectiveness,

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and bring to light key insights that could guide the design of fire policies fit for future novel climate conditions. We propose adaptive landscape management focused on the reduction of fire negative impacts rather than on the elimination of this disturbance from the system.

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1. Introduction

Fire regimes have been changing during the last decades around the world (Bowman et al., 2011; Fréjaville and Curt, 2015; San-Miguel-Ayanz et al., 2013; Schoennagel et al., 2017). In many regions, anthropogenic influences are behind such changes: a combination of land-use changes, human-induced climate warming and changes in fire suppression has pushed fire regimes to be more dominated by uncontrollable weather events (Duane et al., 2019; Moreira et al., 2001; Pausas and Fernández-Muñoz, 2011; San-Miguel-Ayanz et al., 2013). Investment in fire suppression has been the main strategy implemented by many governments to control wildfires. While these strategies have succeed in reducing some fire impacts, they have generally failed in regulating large intensity fires in most situations (Fernandes, 2013; Moritz et al., 2014; Schoennagel et al., 2017; Tedim et al., 2016). In addition, fire regimes are expected to further change with global change, with important consequences for humans, biodiversity, ecosystem resilience and associated ecosystem services (Amatulli et al., 2013; Pausas et al., 2008; Westerling et al., 2011). In Mediterranean ecosystems, several studies predict increases in fire activity to the end of the century (Amatulli et al., 2013; Batllori et al., 2013; Turco et al., 2018a). There is a call pleading for the implementation of ecosystem and fire management actions to help override or mitigate current trends (Fernandes, 2013; Khabarov et al., 2014; Thompson and Calkin, 2011) and future expected negative fire regime impacts.

Climate change is one of the most important drivers of ecosystem change forecast for the 21st century (Aponte et al., 2016; Millar et al., 2007; Moritz et al., 2012). Its effects are largely beyond the control of local management agencies and it can have strong impacts on fire regimes due to the projected increases in temperatures and precipitation variability (Batllori et al., 2013). Many studies have demonstrated that, beyond temperature and precipitation, atmospheric circulation types play an important role on fire activity (Duane and Brotons, 2018; Pereira et al., 2005; Ruffault et al., 2016). These circulation types reveal other relevant factors such as barometric gradients and atmospheric stability, with direct influence on wildfire development (Rothermel, 1991). Evaluating how these general conditions will evolve in the future can bring to light 'novel' climate situations that in turn may shift fire activity from its historical range of variability to novel fire regimes (Schoennagel et al., 2017). Understanding and anticipating ongoing climate change is therefore critical to forecast potential fire activity and eventually help to guide the development of fire management strategies that reduce fire negative impacts.

Fire management is and will continue to be key to offset increasing burnt area trends associated with climate change (Khabarov et al., 2014; Moritz et al., 2014). During the last decades, increases in fire suppression efforts have been the backbone of fire management policies developed in many countries but often with counterintuitive effects: strong fire suppression has promoted extreme wildfire events under adverse weather conditions because of fuel build-up at the landscape scale (Duane et al., 2019; Minnich, 1983). Alternative fire management strategies have been identified as crucial to control wildfire events under worsening climates (Calkin et al., 2015; Khabarov et al., 2014). The exploration of fire management options has also targeted fuel management as a major avenue to reverse negative climate impacts and promote fire resilient ecosystems (Hessburg et al., 2016). Additionally, fire management cannot turn a blind eye to ongoing unplanned wildfires: it is crucial that adaptive management strategies are developed accounting for ongoing processes to ensure effective decisions. Policies that promote fire smart landscapes and adaptive resilience to wildfire by which people and ecosystems reorganize in response to changing fire regimes are strongly recommended (Schoennagel et al., 2017).

Fuel reduction created by prescribed burning (PB) has been advocated as a possible alternative to strong fire suppression policies (Fernandes et al., 2013). PB is the planned use of fire to achieve defined objectives. There is still a debate about the suitability, effectiveness and preparedness of its implementation (Fernandes et al., 2013; Price et al., 2015). Moreover, although much work testing PB effects at local scales has been carried out (Alcasena et al., 2017; Valor et al., 2015), few studies have quantified the effects of PB at the fire regime over the long-term, nor the amount needed to remain under sustainable thresholds required in different biomes and socio-ecological contexts (Price et al., 2015). PB effectiveness is difficult to quantify because it depends on: 1) how long a treated area remains as a low-fuel area; 2) the probability of a fire to pass through within the time that the treated area remains as a low-fuel, and 3) the behavior of a given fire arriving at that area (i.e. wind-driven, convective, etc.). Furthermore, fire management targeted to reduce fuel could benefit from already ongoing wildfires: management costs could be reduced by letting these fires burn under controlled conditions. Although similar to PB, consequences of this kind of management strategy are uncertain under warming climates. Evaluation of the applicability of alternative fire management strategies requires quantitative assessments that can reveal the real effectiveness on wildfire hazard reduction under future climates (Khabarov et al., 2014).

Landscape dynamic models are pivotal tools that allow us to anticipate medium and long term effects of fire management strategies under climate change. Such models require the incorporation of key ecological, anthropogenic and climatic processes that interact across temporal and spatial scales. Although we now have a good knowledge of the processes driving fire activity (e.g. fuel, climate, suppression), our ability to integrate this information into spatially explicit modelling tools that allow the projection of these systems under future global change scenarios is still scarce (Gil-Tena et al., 2016; Titeux et al., 2016).

In this work, we aimed at anticipating the effects of different fire management strategies on future fire regimes under changing climatic conditions. Our first goal was to project impacts of future climate change on the total burnt area, location, intensity and variability of fires during the 21st century and under current fire management levels. Then, using a landscape modelling approach, the following hypothesis were tested: 1) Burnt area will increase under climate change; 2) PB can modify fire regimes by decreasing high-intensity unplanned fires; 3) PB impact will be higher if targeted in high-risk areas rather than in other defensive locations; 4) PB plans adapted to ongoing fire activity will increase its efficiency; and 5) A 'let it burn' strategy can mimic the PB strategy with lower efforts. For testing these hypotheses we developed an extended version of the spatially explicit fire-succession MEDFIRE model (Brotons et al., 2013) and applied it to Catalonia (NE Spain), a densely populated Mediterranean region covered 60% by forest, which has experienced strong changes in fire regimes during the last decades due to changes in land-uses and settlement patterns, rural abandonment, and high investments in fire suppression and prevention. An intense debate on the applicability of fuel-control policies exists in the region, but there is a lack of knowledge on how this can be effective in the face of uncertain changing climates.

2. Materials and methods

2.1. Study area

Catalonia (NE Spain, 32,000 km^2) is a Mediterranean region with hot dry summers, rainy springs and falls, and mild winters. Catalonia has a complex relief that greatly affects weather dynamics, with precipitation and temperature variability related to distance-to-sea and altitude (Lana et al., 2001). The Pyrenees, a major mountain east-west oriented range in the North of the region, strongly affects climate variability (Soriano et al., 2006). Average wind speed in the northern and southern Catalonia is higher than in the center (Gencat, 2004). Sixty percent of the study area is covered by forests and shrublands. Dominant tree species are pines (*Pinus halepensis* (21%), *Pinus sylvestris* (16%), *Pinus nigra* (9%), *Pinus uncinata* (5%) and *Pinus pinea* (3%)) and oaks (*Quercus ilex* (17%) and *Quercus suber* (5%); Ibàñez and Burriel, 2010). Fire return intervals in Catalonia for the period 1980–2000 range from 60 to >400 years for homogeneous fire regions of around 45,000 ha (Pique et al., 2011). Annual burnt area is highly variable, with the largest areas burnt in 1986 (65,000 ha) and 1994 (82,000 ha), and most fires occur in summer (June–September). Stand-replacing fires are the most widespread type of fire in Catalonia, with >85% of the burnt area being affected by crown fires (Rodrigo et al., 2004). The prevalent fire management strategy in Catalonia is strong fire suppression, and firefighting investment has increased six-fold since the early 1980s (Otero and Nielsen, 2017). A decreasing trend in the number and size of fires has been observed after the large fires occurred in 1986 and 1994, mainly explained by an increase in fire prevention and suppression (Brotons et al., 2013; Duane and Brotons, 2018; Turco et al., 2013).

2.2. The MEDFIRE model

The MEDFIRE is a landscape dynamics fire-succession model that simulates spatial interactions of multiple ecological and human-driven processes shaping land-covers and influencing vegetation dynamics. The model has already been applied to assess the role of different fire regime drivers (Aquilué et al., 2019; Brotons et al., 2013) and to evaluate vegetation and fire regime dynamics under future conditions (Gil-Tena et al., 2016; Regos et al., 2014). Here, we developed an updated version of the model aimed at exploring fire regime dynamics under the interaction of multiple drivers: climate, fire management (i.e. relaxed fire suppression and planned prescribed burns) and fuel accumulation processes (i.e. afforestation and forest aging). This version of the model does not consider other land cover changes even though we can expect substantial changes between now and 2100.

The MEDFIRE model simulates the dynamics of two spatial state variables: 1) Land-Cover Forest type, that describes the main land-covers and tree dominant species in forest areas; and 2) forest age, that tracks the age of forest species and shrublands. Spatial resolution is 1 ha and temporal resolution is 1 year. A brief description of the model's two modules (i.e. fire and vegetation dynamics) are detailed below.

2.2.1. The fire dynamics module

Fire dynamics component of the MEDFIRE model consists of two sub-modules: the wildfires sub-module and the prescribed burns sub-module. In the wildfire sub-module, fire regime is simulated as an emergent landscape-scale property. Annual burnt area, fire sizes, fire shapes and fire intensity are the emergent fire regime descriptors that arise from model interactions. In the prescribed burns sub-module, controlled fires are generated to eventually impact wildfire regime.

2.2.1.1. The wildfire sub-module. Wildfires are simulated under different 'Synoptic Weather Conditions' (SWC). These are categorizations of atmospheric weather depicting short-term weather conditions (hours to days) at large continental scales. SWC have been shown to drive several fire regime attributes such as fire size, location or fire spread (Duane and Brotons, 2018). Adopting a SWC-based framework integrates relevant weather-factors influencing coarse spatial fire patterns while avoiding the need of detailed weather data at fine scales. Fires occurring under the different SWC are simulated independently from each other and all follow the following steps:

Potential climatic burnt area. The model starts by determining the climatic potential for fire activity for a given year. Potential climatic burnt area (in hectares) represents the sum of fire-weather windows in a summer that are conductive to fire. This potential depends on SWC and on medium-term weather conditions (~weeks or months) that influence potential burnt area by making fuels more available, thus increasing fire spread and eventually promoting larger fires. Medium-term weather conditions are classified into two categories defining the climatic severity of the year. Annually, the model estimates a potential climatic burnt area from a probability distribution that depends both on the SWC and the climatic severity of the year. Once a potential climatic burnt area is set, the model sequentially simulates as many fires as needed until that area is reached.

Fire ignition, spread and potential fire size. For each fire, an ignition point is chosen according to an ignition probability map that is then masked by each SWC. Then, for each fire, the model selects a fire spread pattern that can depend either on SWC alone, or also on fuel landscape accumulation (Duane et al., 2015). In the latter case, landscape properties and their potential capacity to sustain very-intense fires (i.e. convective fires) are evaluated in a buffer around the ignition point. Fires propagate according to different fire spread patterns that modulate the relative role of factors influencing fire spread (wind, slope, aspect and species flammability; Duane et al., 2016). Fires propagate until reaching a potential fire size. Potential fire size of each fire is previously drawn from a fire size distribution that depends on the fire spread pattern and the climatic severity of the year.

Fire suppression. Fire fronts can be suppressed. In these cases, the potential fire size is not reached, and the unburnt hectares are added to the potential climatic burnt area. Fire suppression depends on the fire spread pattern and it follows two different strategies: active and opportunistic. In active fire suppression, fire fronts are stopped when fire intensity is low enough to be controlled by firefighters. Since fire brigades are not able to immediately start suppression when fire intensity decreases, it is necessary to concatenate a number of consecutive cells of low- intensity fire to allow suppression. This fire management strategy mimics fire suppression operations in elevation changes or in low flammable land-uses as irrigated crops. In opportunistic fire suppression, fire fronts can also be stopped if they reach a low-fuel area. In the same way as active fire suppression, the opportunistic alternative starts after fire has burned a minimum number of consecutive low-fuel cells. This strategy mimics fire suppression operations occurring in past fire scars that provide low-fuel areas suitable to operate. All past fires (both wildfires and prescribed burns) can generate fire suppression opportunities. The number of years that past fires remain as suppression opportunities is a model parameter.

Fire effects. Fires stop spreading when they reach their potential fire size or when all fire fronts have been suppressed. Final burnt area and perimeter shape are emergent model outputs that arise from the interaction between fire spread across the landscape and fire suppression effectiveness. Cells burnt can be classified according to fire intensity within the cell: low or high intensity. Fire intensity depends on both fire spread rate and climatic severity. The threshold dividing the two intensities is a model parameter. However, no matter the fire intensity, fires are always stand-replacing and vegetation age drops to 0. Fire intensity is thus a proxy of fire behavior and it is used to understand fire regime dynamics.

2.2.1.2. The prescribed burns sub-module. The model simulates prescribed burns aimed at reducing burnt area through the generation of fire suppression opportunities in preselected, planned sites. There are two possible implementations of prescribed burns: 1) a fixed prescribed burnt area per year or 2) an adaptive prescribed burnt area per year. In the former, the user sets a fixed amount of area to be burnt every year. In the latter, the amount to be burnt is planned considering the areas burnt in the most recent years. This seeks to maximize planned fires effectiveness by taking advantage of what has already been burnt to avoid useless or excessive planned fires. Through this adaptive strategy, the area burnt with prescribed burns per year is emergent and it is only applied if the burnt area in previous years does not reach a user-fixed threshold, otherwise the difference is prescribed to burn. This threshold corresponds to an established value set to attain a desired fire regime (multi-year burnt area mean). The time window that past fires can be used as suppression opportunities and the extent to be burnt are specific model parameters.

As for wildfires, the model simulates as many prescribed burns as necessary to reach the annual prescribed burnt area. The size of planned fires is drawn from a fire size distribution and are initiated according to a probability map. Spatial allocation of prescribed burns can follow any condition the user decides (i.e. target species, protected areas, etc.). Prescribed burns spread according to the formulae proposed by Duane et al. (2016) and correspond to the less intense fire spread pattern. Planned fires always reach target fire size and burn in low intensity.

2.2.2. The vegetation dynamics module

The vegetation dynamics module replicates post-fire regeneration and shrublands colonization by tree-forest species as presented by Brotons et al. (2013) and Gil-Tena et al. (2016). After a fire, a forest species can persist or be replaced according to its post-fire functional trait (resprouter, seeder, serotinous or fire-sensitive; Rodrigo et al., 2004). Additionally, homogeneous forests burnt in the same fire event will partially regenerate by neighboring contagion. Afforestation is a probabilistic process depending on orographic variables and the proportion of mature forest around the shrubland to be colonized.

2.3. Model initialization and parameterization

2.3.1. State variables

State variables were initialized for the year 2010 and cover all the Catalonia region at 1 ha of spatial resolution. Both Land-Cover Forest and Forest Age variables were built by Gil-Tena et al. (2016). Briefly, the 2009 Land Cover Map of Catalonia (Ibàñez and Burriel, 2010) updated by 2010 wildfires serves as the baseline map. In forest areas, dominant species and age were assigned according to National Forest Inventories data and spatial interpolation techniques (i.e. kriging, Gunnarsson et al., 1998).

2.3.2. The fire dynamics module

2.3.2.1. Wildfire sub-module

2.3.2.1.1. Potential climatic burnt area. We estimated the climatic burnt area potential using existing records of annual burnt area in Catalonia before the establishment of the current strong fire suppression policy (year 2000), when fires were mostly stopped after changes in weather conditions (vegetation was plentily available and did not limit fire spread). Observed fires were classified according to the climatic severity of the year (medium-term weather conditions) and weather conditions of their occurrence day (short-term weather conditions, SWC). Short-term weather conditions determine moisture content of dead fuels, wind speed and direction, and atmospheric stability, which eventually regulate fire spread (Rothermel, 1991). Duane and Brotons (2018) found six SWC leading to large wildfire generation in Catalonia. To simplify model building and analyses, we grouped the six SWC into three according to main weather factor that distinguishes them: Wind SWC, Heat SWC and Regular SWC. Medium-term weather conditions in Catalonia strongly impact fire activity (Castro et al., 2003), since they determine the growth of fine fuels and moisture content of soil and live-fuel (Castro et al., 2003; Keeley, 2004), that prompt fire initiation and spread. We used the Standardized Precipitation-Evapotranspiration Index (SPEI; Vicente-Serrano et al., 2010) to assess vegetation dryness conditions, and we set the value found by Duane and Brotons (2018) to separate dry years from mild years (SPEI = -0.21; more details in Appendix A). The model selects the climatic severity of the year from a uniform probability, being 45% of dry years for the calibration period. We then fitted log-normal probability distributions of burnt area potential for each combination of short-term (Wind SWC, Heat SWC and Regular SWC) and medium-term (mild and dry) weather conditions using 1980–2000 as observed data (Table A.1). We checked distribution parameters by SWC using observed proportion of mild and dry years in this period (Fig. A.1).

2.3.2.1.2. Fire ignition, spread and potential fire size. In Catalonia, ignition pressure has been related to land-cover variables (higher in heterogeneous landscapes encompassing human and natural covers and close to roads), topography variables and vegetation flammability variables (González-Olabarria et al., 2012; Rodrigues et al., 2014). The probability of ignition was adjusted with a logistic regression (Martínez et al., 2009; Syphard et al., 2008) using landscape variables at 2 km resolution: elevation, slope, precipitation, and four variables related to land-uses: road density within the cell, and dominance of natural covers (forest and shrubs), of wildland urban interface (natural and urban) and of agro-forest interface (natural and agriculture). Since anthropic land uses such as urbanizations or roads remain unaltered for the simulation period, the current model preserves the current fire ignition distribution for the following century. Details on the resulting probability model can be found in Appendix A. For each SWC, an ignition mask is used to exclude areas with low probability for that SWC. The delimitation of masked areas follows current knowledge on the areas of Catalonia prone to be affected by fires linked to a particular SWC (Duane and Brotons, 2018). From their work, we selected areas with more than one fire per 10,000 km^2 to be suitable for the occurrence of each SWC.

For each ignition point the model assigns a fire spread pattern. For ignitions occurring under Wind or Regular SWC, fire spread pattern is directly assigned to wind-driven and topography-driven types, respectively. In contrast, fires occurring under Heat SWC can be either topography-driven or convective, depending on fuel load availability. Duane et al. (2015) found convective fires to be strongly related to forest amount and structure around fire ignitions. We simplified their finding and fitted a logistic model of the probability of becoming a convective fire (in contrast to remaining a topography-driven one) as a function of the proportion of mature Mediterranean pine species 1 km around the ignition (more details in Appendix A).

Fire spread follows the formulae and parameterization presented in Duane et al. (2016) (Eq. A.3). Wind direction of simulated fires was assigned according to the type of fire spread pattern and ignition location (more details in Appendix A). Potential fire size distributions were adjusted for the three fire spread patterns under the two different climatic severity types following Power-law distributions (Table A.2 and Fig. A.2).

2.3.2.1.3. Fire suppression. Fire suppression initialization encompasses active fire suppression and opportunistic fire suppression. For the latter, Duane et al. (2019) found that in Catalonia past fires act as a barrier for fire spread during seven years, although this value is smaller in windy situations. Opportunistic fire suppression worked then until a time when fire interval reached seven years in convective and topography-driven fires, and five years in wind-driven fires. Active fire suppression was calibrated according to burnt area in Catalonia after year 2000. This fire suppression value varied according to the different fire spread patterns, since Duane and Brotons (2018) found that firefighters in Catalonia have become extremely effective in controlling convective and topography-driven fires, but not wind-driven fires. We

thus simulated several values of fire suppression and selected the one that minimized differences between simulated burnt area and observed burnt area for the period 2000–2015 (Table A.4).

2.3.2.1.4. Fire effects. We set the threshold that separates high from low intensity fires by selecting the value that pulled 15% of the cells as low-intensity fires (Rodrigo et al., 2004) in three Catalan fires that occurred in mild years (one per fire spread pattern).

2.3.2.2. Prescribed burns sub-module. Prescribed burn size distribution was adjusted from the current PB database in Catalonia, previously filtered for the 25% larger prescribed burns (distribution parameters are given in Appendix A). Fire spread followed the formulation for topography-driven fires, the more controllable type for firefighters in Catalonia. Prescribed burns could only be applied if a cell's age was older than 30 years, both 1) to ensure that stands would have reached reproductive maturity (Zagas et al., 2004), and 2) to apply burns in mature forest structures that allowed controlling fire intensity of future events (Taylor et al., 2014). In the case of shrublands, this premise was also applied, given that later stages of the succession after fire of Mediterranean shrublands show lower proportion of dead biomass and burn in a lower intensity (Baeza et al., 2011).

2.3.3. The vegetation dynamics module

Vegetation dynamic parameters were obtained from Gil-Tena et al. (2016): the probability of post-fire regeneration matrix followed the results from Rodrigo et al. (2004), and the probability of afforestation followed a logistic regression calibrated for the study area according to vegetation, climate and topography variables.

2.4. Scenario definition

We explored the effects of different fire management practices on fire regime under changing climate conditions (Fig. 1 and Table 1). The sources of variability between scenarios were climate, fire management strategy and the spatial allocation of such management. Climate change can influence fire regime by increasing climatic potentials and decreasing low intensity fires, while any fire management scenario is supposed to play a role on fire regime by mainly influencing opportunistic fire suppression.

2.4.1. Climate change scenario and novel extreme fire prone conditions

The climate scenario was framed within the Representative Concentration Pathways (RCPs) built for the assessment report on climate change IPCC5 (Moss et al., 2010). We used RCP 8.5, the worst-case scenario forecast for the end of the 21st century. High-end climate scenarios like the RCP 8.5 are generally considered to be more realistic under current greenhouse emission rates (Beaumont et al., 2008; Raupach et al., 2007). This scenario is characterized by increasing greenhouse gas emissions over time, leading to high greenhouse gas concentration levels which reach an average temperature increment of 3.7 °C by the end of the 21st century (Riahi et al., 2007). We used data from the model UKMO-HadGEM-CC (Collins et al., 2011; Martin et al., 2011) including short- and medium-term variables needed to calculate medium-term and short-term weather indices from nowadays to 2100. We calculated medium-term weather conditions of the future by computing the SPEI index of the 3-months prior to July each year (we used functions from R-package 'SPEI'; Beguería et al., 2014). We split the overall temporal extent of simulations (from 2011 to 2100) into three periods (2011–2015 (observed), 2016–2060 and 2061–2100), and calculated for each period the percentage of dry years (more details in Appendix B).

2.4.1.1. Projected novel climate extreme fire prone conditions. Climate is expected to change in the future and bring novel conditions that might violate our current assumptions about the relationship between climate and fires (Amatulli et al., 2013; Khabarov et al., 2014; Schoennagel et al., 2017; Westerling et al., 2011). Projected novel climates were identified according to future climates (combinations of weather variables) not recorded in the past because of the higher temperatures projected for the future. We therefore classified future days

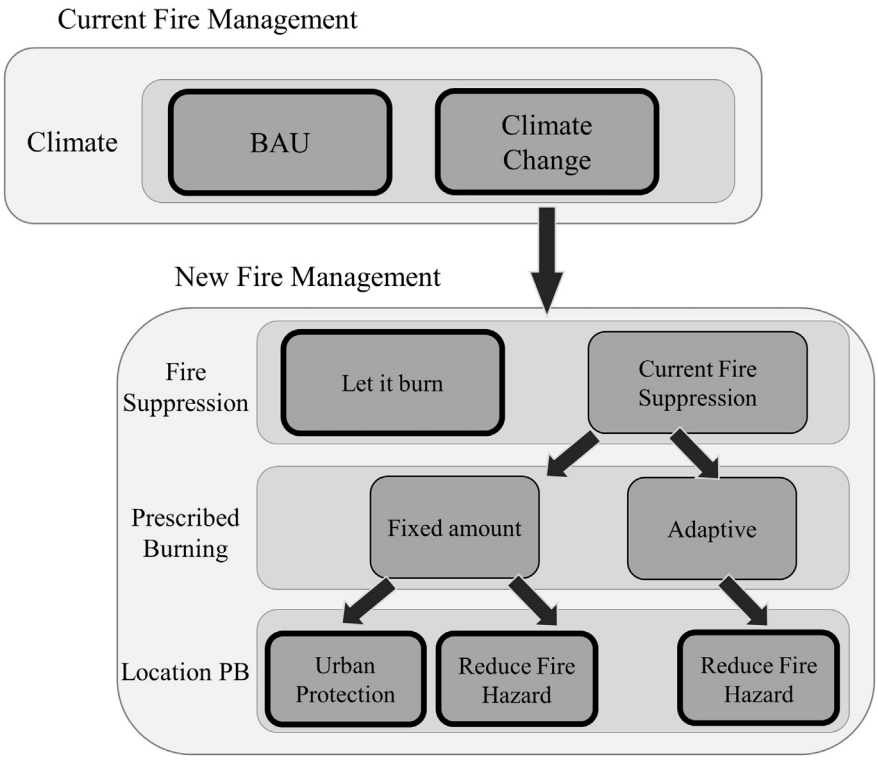

Fig. 1. Nested scenario definition according to different scenario elements. Width-border squares identify the combination of drivers used in the six proposed scenarios (BAU: Business-as-usual, PB: Prescribed burning).

Table 1
Details of the climatic and fire management scenarios used in the present work (BAU: Business-As-Usual; PB: Prescribed burning; RCP: Representative Concentration Pathway).

Scenario name	Climate	Fire suppression	Planned fires	Rationale and scenario details
BAU	Current	Current	No	This scenario assumes that both current suppression efforts and current climate will persist in the future. We used this as the baseline scenario.
Climate change	RCP 8.5	Current	No	This scenario simulates fire dynamics assuming that current fire suppression efforts will not change over time and climate will change following a high-end emissions scenario.
Let it burn	RCP 8.5	Relaxed	No	In this scenario fire suppression efficiency is relaxed with the idea of increasing opportunities for fire suppression. Active fire suppression of topography-driven fires (the most controllable for firefighters) was fully removed. Active fire suppression for convective fires decreased to the same levels of wind-driven fires. Fire activity was simulated under a high-emission climate scenario.
FixPB and ReduceFireHazard	RCP 8.5	Current	15,000 ha/year	This scenario simulates a PB program seeking to reduce the extent of unplanned wildfires under a high-end emissions scenario. The amount set (15,000 ha/year) was established after preliminary analyses and after discussion with local stakeholders, and aims at reproducing a realistic extent of planned fires in Catalonia (Alcasena et al., 2017; Salis et al., 2016). Prescribed burns were located in similar locations to areas of high ignition probability, aiming to increase opportunistic fire suppression in areas highly exposed to wildfires.
FixPB and UrbanProtection	RCP 8.5	Current	15,000 ha/year	This scenario simulates a PB program seeking to safeguard communities from fire under a high-emission climate scenario. The amount set (15,000 ha/year) was established after preliminary analyses and after discussion with local stakeholders, and aims at reproducing a realistic extent of planned fires in Catalonia (Alcasena et al., 2017; Salis et al., 2016). Prescribed burns were mainly located close to urban areas.
AdaptPB and ReduceFireHazard	RCP 8.5	Current	Adaptive	This scenario simulates a PB program seeking to reduce the extent of unplanned wildfires by efficiently optimizing prescribed burns. The amount of annual prescribed burn area derives from what was previously burnt. We targeted an "optimal" burnt amount per year: the same than in 2000–2015 decade (7000 ha/year on average) plus 15,000 ha /year, that is: 22,000 ha/year. The model tracks the total burnt area in the previous 7 years (years that past fires suppose an opportunity for fire suppression), and applies PB until 22,000 ha/year x 7 years = 154,000 ha are reached. Prescribed burns were located according to wildfire ignition probability, aiming to increase opportunistic fire suppression in areas highly exposed to wildfires.

according to barometric gradients only (sea level pressure and wind) with function vegclass from package Vegclust (De Caceres et al., 2010). Then, we examined the temperature of each of these classified days to determine whether they belong to the 'novel climates' typology (more details in Appendix B). 'Novel climates' corresponded thus to Hot-Wind SWC and Hot-Heat SWC, and were associated to new extreme weather conditions conductive to intense fires (Flannigan et al., 2009).

How explicitly novel climates will influence fire regimes is challenging because these conditions occur outside the range of historical records. Here we applied the following procedure to estimate the effects of novel climates on 1) potential climate burnt area and 2) fire suppression. Novel conditions are hotter and drier than past conditions, so larger potential burnt areas are expected to occur (Amatulli et al., 2013; Cardil et al., 2015). We adjusted two more climate potential distributions for years belonging to this new class of 'extreme' conditions, one for Hot-Wind SWC and the other for Hot-Heat SWC according to literature: Amatulli et al., (2013) found a peak on future fire activity around 80% larger than the past based on temperature variables for EU-Mediterranean countries; Jin et al. (2014) found that fires occurring under Santa Ana winds in California were ~230% larger than fires occurring under Non-Santa Ana winds. These extreme potential distributions occurred if a year was classified as dry and if the proportion of Hot-Heat SWC or Hot-Wind SWC was high. We assumed that an extreme year occurred when number of novel climates exceeded four days in the same summer (Appendix B). Under novel climates leading to extreme years, suppression capacity for convective fires is predicted to collapse, since it may be compromised due to wild-land urban interface attendance, extreme fire spread and intensity or fires' simultaneity (Gill and Allan, 2008). We therefore adopted the current lower efficiency observed for wind-driven fires (Appendix B).

2.5. Model simulation and data analysis

We ran 100 simulation replicates of the six scenarios from 2011 to 2100. From 2011 to 2015, the model burnt the actual burnt areas in Catalonia. Response variables were: 1) yearly and total burnt area per SWC and prescribed burns; 2) yearly and total burnt area - burnt in either high or low intensity fire; 3) temporal variability of unplanned fires, computed as the range between maximum and minimum burnt areas over a 7-years moving window; and 4) recurrence at the cell-level (mean times-burnt across all the replicates) of high- and low-intensity fires, and convective and wind-driven fires. Finally, we reported Fire Return Intervals (FRI) per homogeneous fire zones (regions of about 45,000 ha delimitated with river basins that share similar fire regime and vegetation characteristics; Pique et al., 2011). These zones have not been used for any previous modelling step, but they are useful to understand changes on fire regime. Fire regime attributes were plotted against time with smooth loess curves.

3. Results

3.1. Future climate and novel fire conditions

The RCP 8.5 scenario predicted the appearance of novel climate conditions for Catalonia. Temperatures within days classified as 'novel climates' were significantly higher than in historically observed SWC (Fig. 2). Moreover, the frequency of these situations changed over time according to the SWC typology: while Hot-Heat SWC days steadily increased from 1 to 2 to ~18 days per year at the end of the century, Hot-Wind SWC days doubled the number of Hot-Heat SWC from ~2060 to 2100 (Fig. 3).

3.2. Climate change effects on fire regime

Climate change impacted burnt area potential (Fig. 4). These effects differed among synoptic weather conditions. Climate burnt area potential of both Heat SWC and Regular SWC increased approximately 60% with respect to the BAU scenario. The increase was especially evident in the second half of the assessed period. The Climate change scenario also predicted a 280% increase in climate burnt area potential for Wind SWC.

Actual burnt area differed substantially between BAU and Climate change scenarios (Fig. 5). Since fire management was the same in both scenarios, differences in final burnt area were due to increases in climate burnt area potentials. However, under Heat SWC, predicted burnt area was much larger in the Climate change than in the BAU scenario because the model assumes that fire suppression capacity decreases in extreme years. It is worth to note that this increment of burnt area can lead to higher fire suppression opportunities, thus

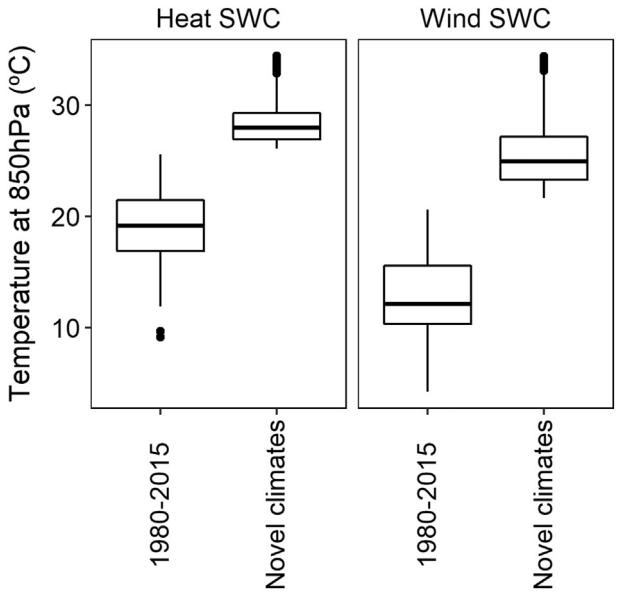

Fig. 2. Distribution of temperatures in Catalonia at 850 hPa within synoptic weather conditions (SWC) for the past (1980–2015) and for the 'novel climates', which have barometric gradients similar to past-SWC but with higher temperatures. Temperatures of novel climates refer to the period 2016–2100.

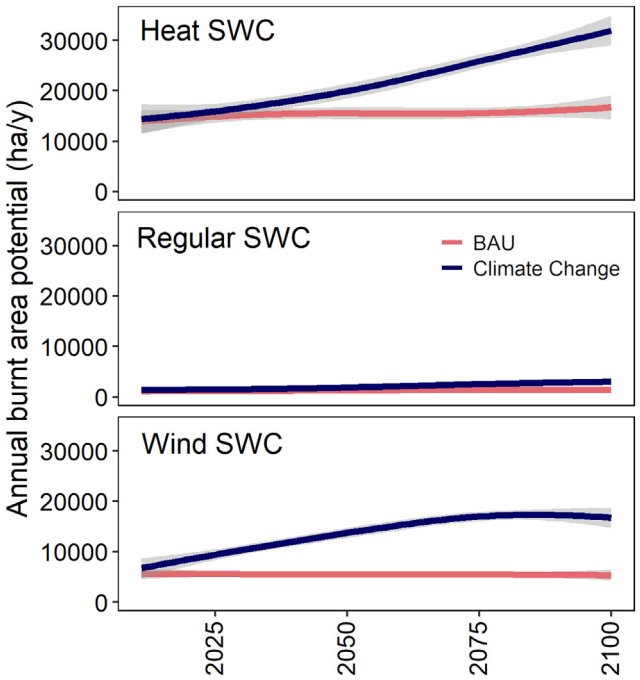

Fig. 4. Changes in the climatic burnt area potential from 2016 to 2100 of each synoptic weather condition (SWC) in the baseline scenario (BAU) and the Climate change scenario. Lines correspond to the 'loess' fit. Shaded areas indicate the 95% confidence interval.

counteracting the increasing climate burnt area potential. This explains why the increase in predicted burnt area in Wind SWC levels-off at the end of the century in the Climate change scenario when compared to the climatic burnt area potential.

3.3. Fire management effects on fire regime under climate change

Burnt area varied under the different management scenarios (Fig. 6). The 'Let it burn' scenario entailed the largest burnt area under the Heat SWC and Regular SWC. In contrast, in this scenario, predicted burnt area under Wind SWC was smaller than when assuming Climate change with current management, because opportunistic fire suppression took advantage of larger burnt areas from the other fire typologies. Burnt area decreased in all scenarios with PB for the three SWC. Fixed PB aimed to reduce fire hazard was the most effective PB scenario, followed by fixed PB aimed to protect urban houses, and finally adaptive PB (Fig. 6). Nonetheless, the total amount of PB was considerably smaller in adaptive PB (1,100,326 ha) than in the other two PB scenarios (1,350,000 ha, Fig. 7).

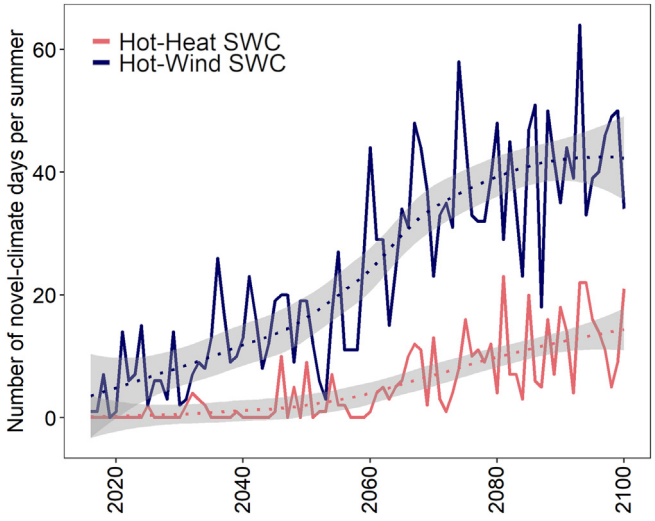

Fig. 3. Changes in the number of novel climate days per summer from 2016 to 2100 for two specific synoptic weather conditions (Hot-Heat SWC and Hot-Wind SWC).

The three scenarios with PB predicted the largest total burnt areas (by both unplanned and planned fires) across the simulation period (Fig. 7). Among these, the fixed PB and urban-protect scenario exhibited the largest burnt area: it was less effective in reducing high-intensity burnt areas than the two other PB scenarios. However, the 'Let it burn' scenario led to the largest high-intensity burnt areas (Fig. 7). The Climate change scenario predicted the second largest amount of high-intensity burnt areas. Adaptive PB was next, because under this strategy unplanned fires were more common than in other fixed PB strategies. Total low-intensity burnt areas mostly captured prescribed burns (low intensity burnt areas were rare under Climate change).

Fire management also influenced the interannual variability of unplanned fires. Variability here refers to the average (across the century) of the difference between maximum and minimum burnt areas by unplanned fires in 7-year time-windows, and aims to capture the occurrence of extreme wildfire events (Fig. 8). Scenarios with PB reduced the total variability in relation to the climate change scenario, specifically the one with Fixed PB aimed at reducing fire hazard. The 'Let it burn' scenario had the largest variability. Interannual variability for one single simulation per scenario is shown in Figs. C.1 and C.2.

Climate change decreased the FRI with respect to the BAU scenario (Fig. 9). In contrast, fire management scenarios considering PB increased the FRI in relation to the Climate change scenario. The 'Let it burn' scenario induced the smallest FRI. Predicted spatial patterns of FRI varied among all scenarios and within scenarios, with smaller FRI consistently identified in southern, central and north-eastern Catalonia.

The recurrence of high- and low-intensity fires (mean of the times that each cell was burnt by across all the model replicates) was assessed per scenario (Figs. 10 and 11). Values for high-intensity burnt areas reached up to 4.3 for the 'Let it burn' scenario, meaning that a pixel burns 4.3 times in the whole period on average. The six scenarios displayed spatial variations of fire recurrence, with higher incidence in

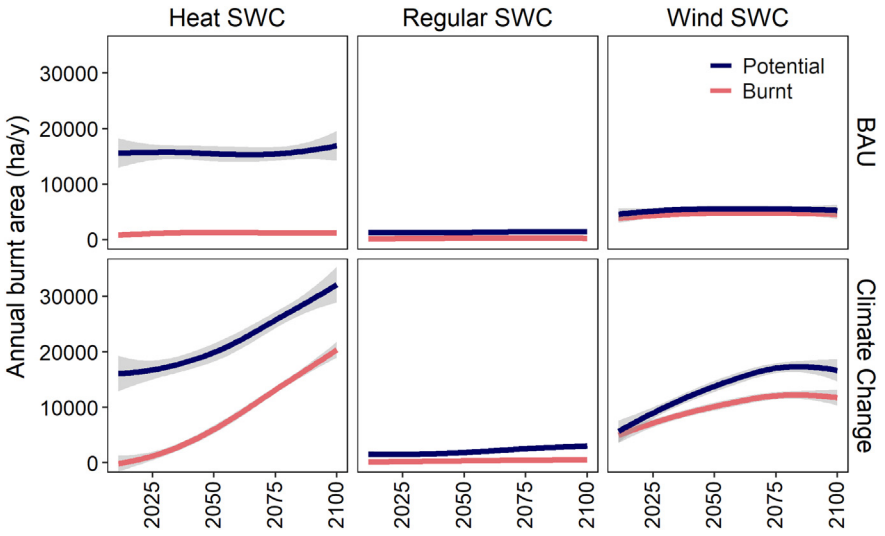

Fig. 5. Changes in climatic burnt area potential and actual burnt area from 2016 to 2100 under each synoptic weather condition (SWC) in baseline scenario (BAU) and the Climate change scenario. Solid lines correspond to the 'loess' fit. Shaded areas indicate the 95% confidence interval.

central and southern Catalonia. For the low-intensity burnt areas, recurrence values only reached 2.5 because prescribed burns were only targeted to forests older than 30 years, so in the whole period the same forest could not burnt more than three times. Spatial incidence of low-intensity fires varied mostly in the 'FixPB and UrbanProtection' scenario, in which PB are applied in all over Catalonia, in contrast with the other PB scenarios in which PB are applied in southern, central and northeastern Catalonia.

The recurrence of convective fires (Fig. C.4) under the Climate change and the 'Let it burn' scenario marked some displacement to areas usually not affected before (i.e. Northwest). High-recurrence in more typical convective fire areas inhibited the accumulation of enough fuel to allow convective fires to return and thus move to other locations (illustrative example of a single simulation in Fig. C.3). The recurrence of wind-driven fires (Fig. C.5) displayed strong incidence in southern and northeastern Catalonia.

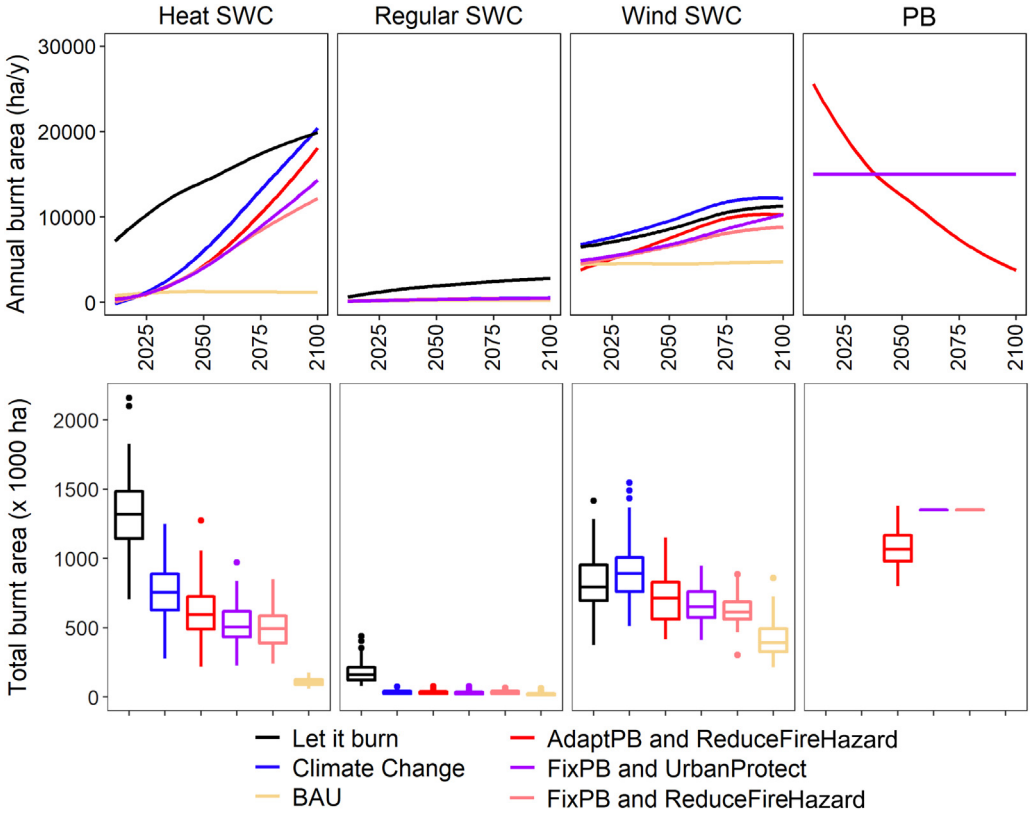

Fig. 6. Changes in annual burnt area under each synoptic weather condition (SWC) and prescribed burns from 2016 to 2100 (upper panel) and totals (lower panel) for each of the six scenarios assessed (Table 1). Prescribed burning (PB) results are only shown where applicable. Lines in the upper panel correspond to the 'loess' fit, and shaded areas indicate the 95% confidence interval. Boxplots in the lower panel show burnt area distributions. (BAU: Business-As-Usual).

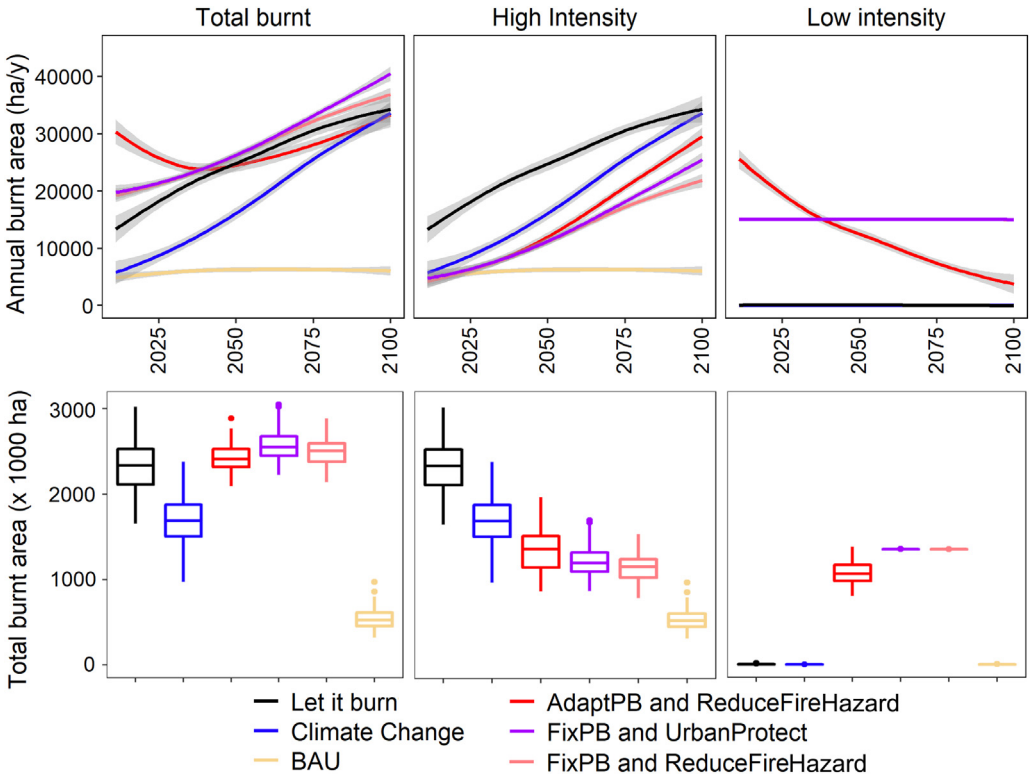

Fig. 7. Changes in total, high-intensity and low-intensity annual burnt area from 2016 to 2100 (upper panel) and totals (lower panel) for each of the six scenarios assessed (Table 1). Lines in the upper panel correspond to the 'loess' fit, and shaded areas indicate the 95% confidence interval. Boxplots in the lower panel show the distribution of values. (BAU: Business-As-Usual; PB: Prescribed burning).

4. Discussion

Here we provide quantitative evidence of the capability of PB to modulate fire regimes under changing climatic conditions. Climate change leads to an increase of fire-weather conditions provoking larger burnt areas and higher intensities than those predicted by the BAU scenario. Fire management has the opportunity to override the expected growing negative fire impacts by increasing the amount of controlled low-intensity fires. By fostering low-fuel landscapes, fire regimes can become less dependent on extreme weather conditions and minimize public losses or shifts towards less resilient ecological states. Moreover, we also showed that certain management strategies are more cost-efficient when these are adapted to dynamic changes of the system.

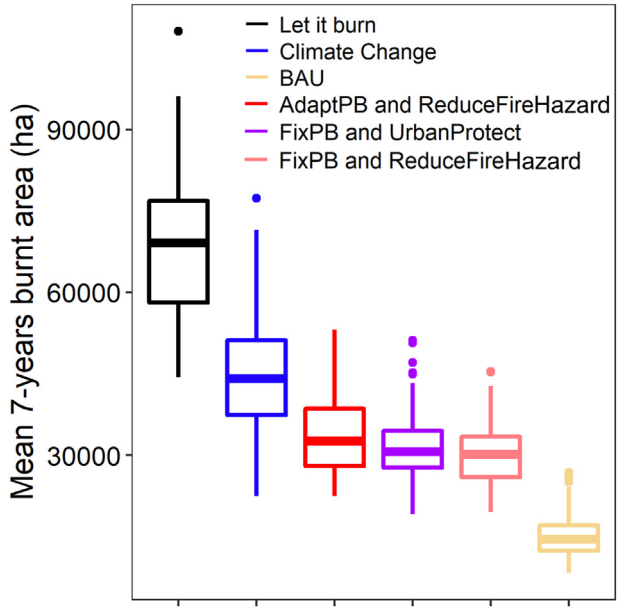

Fig. 8. Total interannual variability of area burnt in high-intensity for the six scenarios (Table 1). (BAU: Business-As-Usual; PB: Prescribed burning).

4.1. Novel climate conditions, and feedbacks between climate, landscape and fires

We have assessed future climate conditions and characterized the presence of 'novel climates' not seen before. Predicting future fires with data outside the historical records surpasses established fire-climate relations. This study aligns with recent findings (Amatulli et al., 2013; Turco et al., 2018b) pointing to an increase of weather conditions conductive to fire in many Mediterranean regions: climate will be hotter and drier (IPCC, 2014). Our results provide significant advances in the understanding of how the increase in climate burnt area potential may eventually influence fire regimes: the negative fire-vegetation feedbacks derived from the interaction with landscape characteristics and fire suppression reveals a leveling-off of burnt area at the end of the century (Fig. 5). Larger burnt areas associated with greater climate burnt area potentials will limit subsequent fire activity because of the leverage effect (Duane et al., 2019). Self-regulating fire processes will be crucial to explain fire activity in a climate change context with increased climate burnt area potential.

Importantly, the impact of climate change will differ according to the different types of fires. While under the BAU scenario most of burnt area corresponds to fires occurring under windy conditions, burnt area under Climate change scenario is equally distributed among fires occurring under Heat and Wind SWC. Although up to 50% of burnt area potential in Heat SWC is suppressed by firefighters, there are still a large number of convective fires that will escape from firefighters' capacity under extreme climates, which does not occur under the BAU scenario. Simultaneity of convective fires will be one of the big challenges that

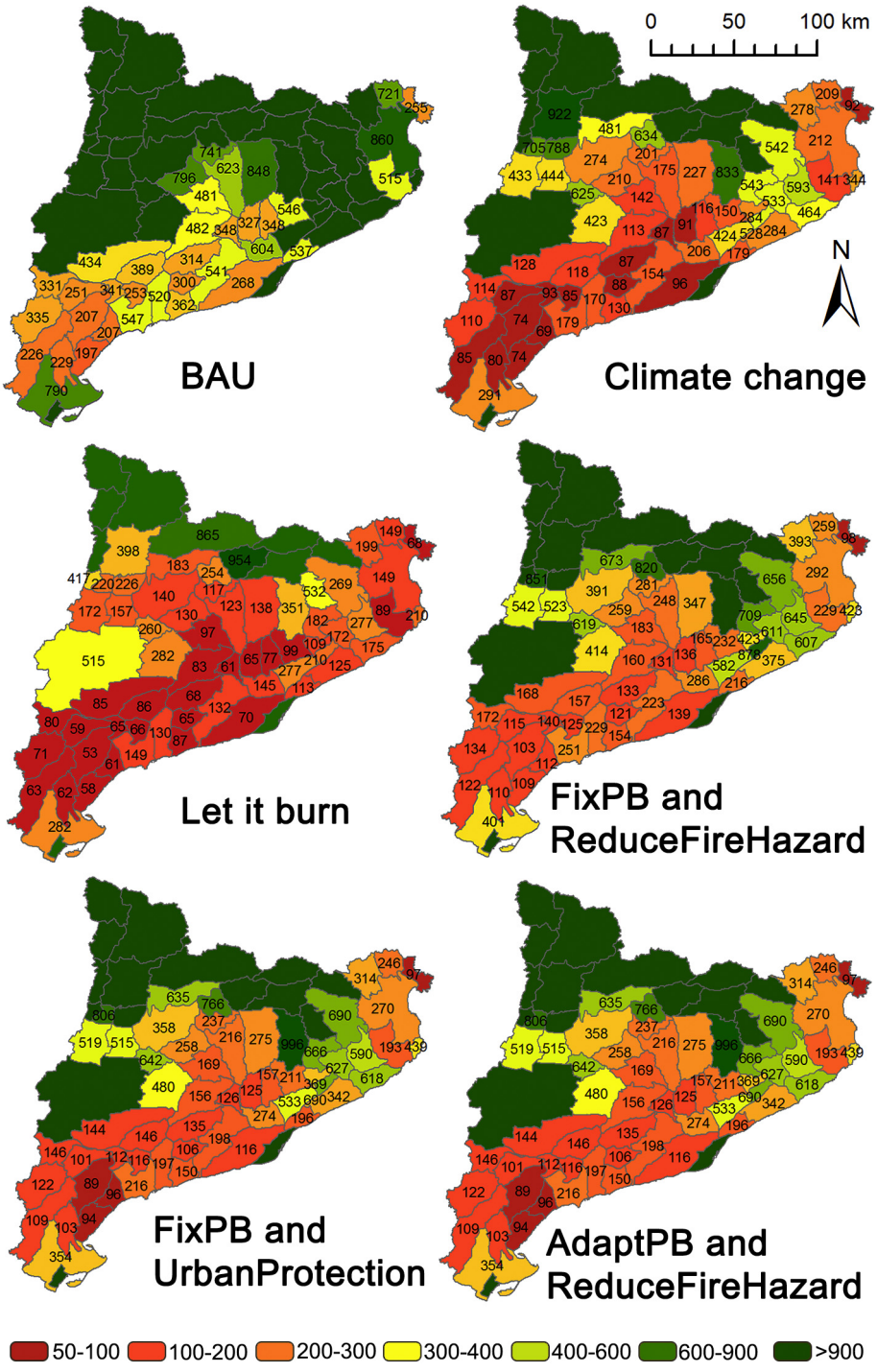

Fig. 9. Fire Return Interval (FRI, in years) per Homogenous Fire Zone for the six scenarios assessed (Table 1). For zones with FRI larger than 900 years the values are not shown because their low fire activity regime gives very large values. (BAU: Business-As-Usual; PB: Prescribed burning).

societies will face under climate change, when extreme fire behavior and unpredictability of wildfire development will compromise people safety (Adams, 2013; San-Miguel-Ayanz et al., 2013; Tedim et al., 2013).

The increased high-intensity burnt area resulting from climate change will likely decrease fire return intervals and increase fire recurrence in the region. The spatial incidence of high intensity fires under climate change will be similar to BAU but extended to new infrequent regions. Notably, climate change will displace convective fires to areas not affected by these fires to date (Fig. C.3). Convective fire occurrence depends on high-fuel landscape accumulation (Duane et al., 2015), which can be compromised in central and southern Catalonia if fire recurrence increases. This is because both the increasing climate burnt area potential and sufficient fuel accumulation will promote the occurrence of large fires in the Pre-Pyrenees, a mountainous area that has not experienced these type of fires yet.

The landscape model presented here is aimed at understanding climate change impacts on fire regimes during the 21st century. However, we have not included some indirect influences of climate change on fire

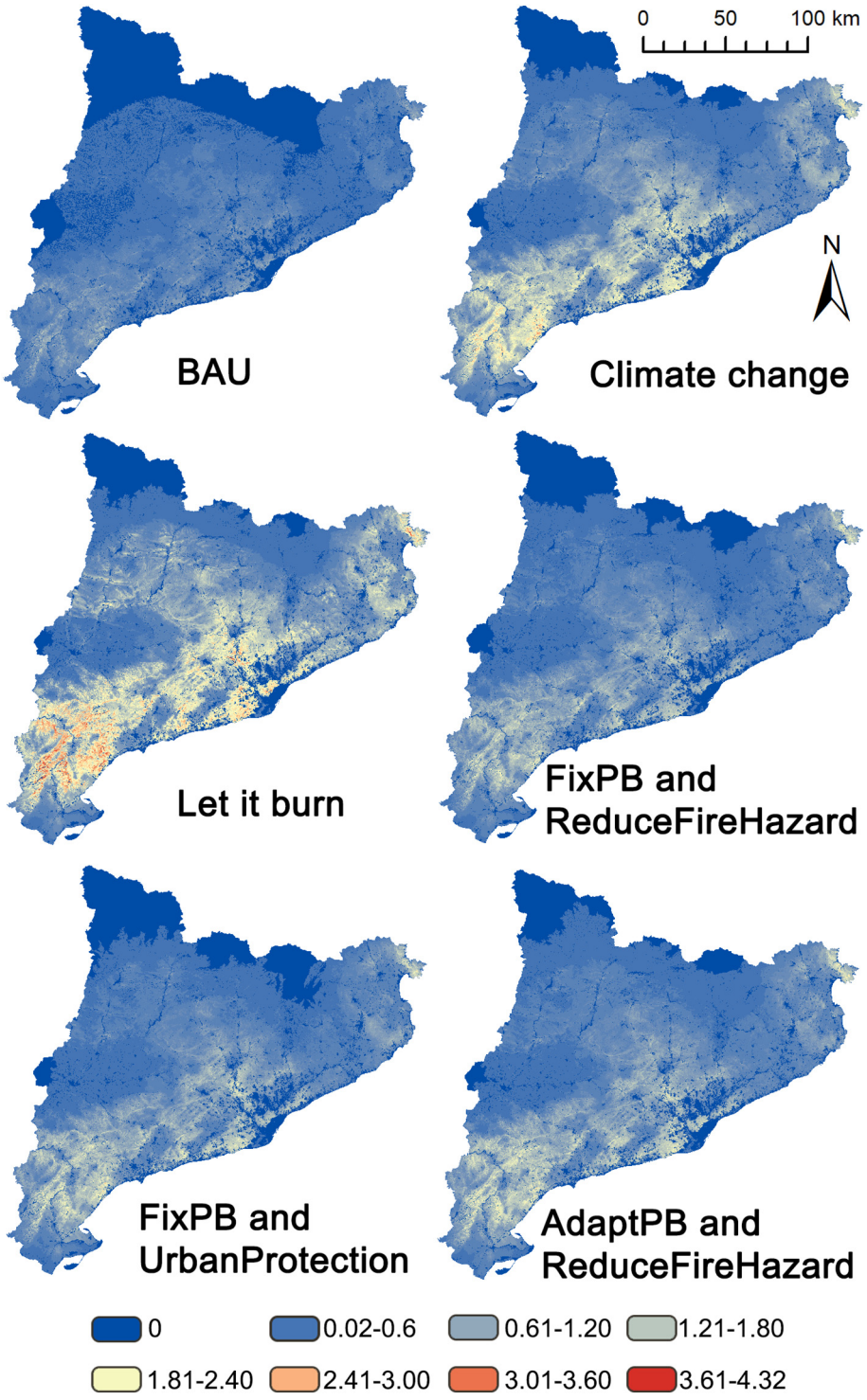

Fig. 10. Recurrence (average of times burnt) of high-intensity fires across all the model replicates during the period 2016–2100 for the six scenarios assessed (Table 1). Dark blue in northern areas correspond to low fire areas in the high Pyrenees, usually not affected by summer fires. (BAU: Business-As-Usual; PB: Prescribed burning).

activity during this period. Climate change will impact ecosystems' productivity and, in return, fire activity potential (Turco et al., 2018b). We have not captured specifically this relationship in this work and further research will be required to disentangle the specific contribution of climate to fire regimes by means of impacts on changing vegetation due to increasing arid conditions (Batllori et al., 2013). Furthermore, the model assumes unalterable configurations of human land-covers along the century and, hence, of wildland urban interfaces, which is not realistic. Given the important role of wildland urban interfaces in the fire initiation, this could re-shape our results on future fire dynamics and spatial fire incidence. Caution must be taken when extrapolating this results to highly dynamic environments, and future research should include the variability of this driver in a more explicit way.

4.2. Fire management impacts on fire regime

In this study, we have quantified the effects of different management strategies on fire regimes. PB led to a large reduction of high-intensity

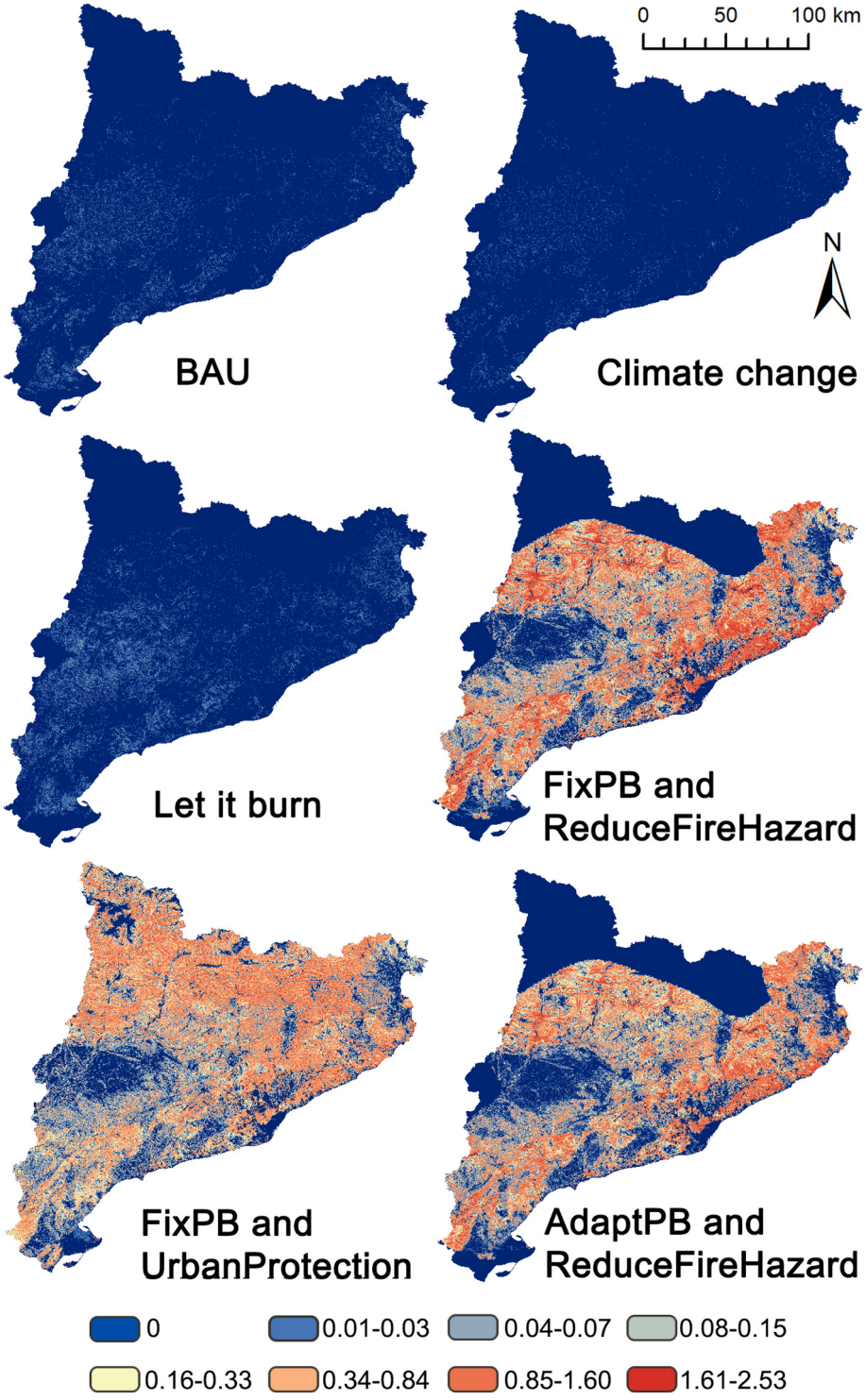

Fig. 11. Recurrence (average of times burnt) of low-intensity fires across all the model replicates during the period 2016–2100 for the six scenarios assessed (Table 1). Dark blue in northern areas correspond to low fire areas in the high Pyrenees, usually not targeted to reduce summer fires. (BAU: Business-As-Usual; PB: Prescribed burning).

burnt areas especially when the preferential allocation targeted to reduce wildfires (instead of other parallel objectives such as protecting urban areas). In contrast, areas burning in low-intensity conditions largely increased. The overall fire extent can remain similar or even increase. High-intensity fires have shown to have strong impacts on biodiversity, soils, water, carbon stocks and eventually human lives (Fernandes et al., 2016; San-Miguel-Ayanz et al., 2013; Tedim et al., 2013). Instead, low-intensity fires have neutral or positive effects on soils and biodiversity, and carbon emissions are much lower (Fernandes et al., 2013). Additionally, PB decreased extreme fire peak activity (Fig. 8). Since extreme large wildfire events can become a social emergency threatening human lives and properties, fire management

targeted to increase the proportion of low-intensity fires can help to solve large wildfire event phenomena and reduce their impacts on ecosystems and people.

Our results suggest that PB management targeted to reduce wildfires has only slightly positive impacts compared to PB targeted to protect urban areas (Fig. 7). Urban settlements are both a vulnerable asset to protect and also a wildfire ignition source (Syphard et al., 2013). When protecting urban areas, management also prevents wildfires to initiate, and so fires burning in high-intensity are also constrained. Since fires occurring in the Wildland-Urban Interface (WUI) require changing suppression tactics – and fire suppression in WUI can represent as much as 95% of suppression costs (Quadrennial Fire Review, 2015)-, reducing wildfires on the wildland-urban interface can further improve overall fire management cost-efficiency. WUI currently emerge as key elements of coupled-systems in which to target management efforts (Moritz et al., 2014).

Moreover, the long-term effectiveness of different management strategies should be considered. Cost-effective analysis is a reliable tool to make comprehensive decisions (Catry et al., 2010; Clayton et al., 2014). In our study, adaptive PB reduced the total extent of PB area by taking advantage of large areas burnt during previous years. High-intensity fire hazard reduction was lesser under this strategy, but more effective in terms of efforts. Policy makers can use this information to reach a consensus of appropriate management strategies that help to achieve desired fire regimes under sustainable investments.

Relaxing fire suppression had a large impact on fire regimes. A number of works have presented this strategy as a way to increase landscape fuel-reduction at a low-cost, taking advantage of already running fires instead of starting new fires with PB (Houtman et al., 2013; Regos et al., 2014; Reinhardt et al., 2008). Although it is a cheaper option than PB (because it takes advantage of the ongoing suppression operative), the implementation of this strategy can have several drawbacks. For instance, our model results suggest that total high-intensity burnt areas may not really diminish. Our model allows unplanned fires to burn in low-intensity during mild years, but given the decreasing amount of mild-weather years, most fire-cells will in fact burn in high-intensity. This can lead to different, generally undesired, consequences for soil, carbon emissions and biodiversity than when applying PB. In addition, the 'Let it burn' strategy does not allow spatial decisions on where to burn, whereas PB strategies let the manager decide where and when. Finally, it is unrealistic that firefighting services will let fires burn near urban areas putting at risk human safety. This strategy could be more plausibly implemented in remote areas where the decision of letting fires burn does not increase the risk of potential negative consequences for human safety and assets.

The spatial incidence of high-intensity fires differed across the management scenarios. Fire recurrence in southern Catalonia was lower under the PB scenarios than under the Climate change scenario compared to the rest of Catalonia. This is explained by the minor prevalence of extreme large wildfires that affect these high-risk areas under the PB management. In contrast, under the 'Let it burn' strategy, fire recurrence increased mostly in high-risk areas, despite the opportunities that past fires offer. Spatial variation of fire effects is of paramount relevance for evaluating forthcoming effects of current scenarios into ecosystems. In fact, the effectiveness of PB could be increased by prioritizing management locations that provide highly-efficient suppression opportunities. These are mainly locations related to specific topographic features (mountain passes, ravine junctions, etc.; Duane et al., 2015). Moreover, PB plans should also be specific for the different species fire-response functional traits. Biodiversity conservation strategies could benefit from the implementation of fire management recipes that emulate fire regimes to which particular species are adapted (for instance, frequent and low-intensity fires for low intensity fire-adapted non-serotinous species such as *Pinus nigra* stands in Catalonia, Rodrigo et al., 2004).

4.3. Fire policy insights under changing climates

We have shown that adaptive PB can have positive impacts in reducing extreme events and high intensity fires. Our model has allowed us to test the effectiveness of PB by incorporating the two main elements modulating PB effectiveness: post-fire regeneration establishment and aging, and fire regime characteristics (frequency, type of fire spread pattern, etc.). The amount burnt in PB in the present work has been discussed as reasonable and feasible (15,000 ha/year; Marc Castellnou, head of firefighters in Catalonia, personal communication), which points to a suitable implementation of this fire management strategy in Catalonia. But PB it is not a panacea. PB has other limitations beyond those of quantifying its proven effectiveness. Around the world and particularly in southern European countries there is a social resistance to accept fire as a management tool (Fernandes et al., 2013), principally from an urban point of view (Otero and Nielsen, 2017). Moreover, managers also find impediments associated to its costs, risk of it escaping out of control, etc. (Altangerel and Kull, 2012). PB will be more efficient and accepted if it can be presented as a multi-objective management tool (i.e. besides decreasing fire extent and intensity, PB can also be used to restore habitats, maintain open forests, improve pastures in mountain areas, facilitate natural regeneration, control spreading of pests and diseases, etc.; Fernandes et al., 2013). In addition, while PB can have indirect positive effects on biodiversity (e.g. by reducing fire hazard and thus decreasing the incidence of high intensity fires), it can also entail negative impacts, and even more in compare to other alternative fuel reduction treatments, such as mechanical treatments. PB can be associated to changes in soil chemical composition (Úbeda et al., 2005), increase runoff (Marcos et al., 2000) and increase post-fire erosion rates (Fernández et al., 2012; Soto and Díaz-Fierros, 1998). PB can also increase fauna mortality (Lyet et al., 2009), and affect vegetation photosynthetic capacity, meristematic and vascular issues, and increase the risk of pathogen attack, eventually provoking an initial or delayed mortality (Valor et al., 2015, 2016). Overall however, available evidence shows a negligible effect of PB on vegetation and wildlife diversity in forested areas (Moreira et al., 2003).

Fire management can be conceived as a way to achieve a certain fire regime that benefits both ecosystems and humans without entailing unnecessary risks. Many studies have demonstrated both that fires are a natural process of many ecosystems that benefit some flora and fauna, and that totally excluding fire from the system is impossible (Moreira et al., 2003; Moritz et al., 2014; Pausas and Keeley, 2009). Fire-related management goals have started to shift from 'total fire removal' to a 'coexistence with fire' (Moritz et al., 2014). To work towards fire regime control, the best pathway to take is to promote fuel reduction at the landscape scale so preventing fire regime to be mostly controlled by climate (Duane et al., 2019; Pausas and Fernández-Muñoz, 2011). Consequently, under projected extreme adverse climate conditions, we can still have the capacity to modify final burnt area through fuel-reduction (Fernandes et al., 2016; Khabarov et al., 2014). Fuel reduction at the landscape scale can be achieved in several ways: by land-use conversion, fuel mechanical treatments, grazing, or controlled fires (by prescribed burns or letting-burn strategies). From all this, while PB does not suppose a reduction of total fire extent, a realistic implementation of PB across the study area (15,000 ha per year) can reduce high-intensity burnt areas and limit mega-fires.

This study provides evidence about the potential of PB as a management tool, but we acknowledge that this fuel treatment is not the only or even necessary the best tool to apply in all cases. Although studies comparing different fuel reduction treatments and their effects at mitigating wildfire hazard are scarce, we suggest PB should be more often considered within the range of potential management options when planning landscape-level fuel treatments. Fuel reduction over large areas by PB can be one of the most efficient methods of the current available measures to mitigate wildfire risk (Altangerel and Kull, 2012; Narayan et al., 2007). Fuel reduction mechanical treatment at

the stand scale has shown to decrease fire hazard in a similar way than PB (Fernandes et al., 2013), but fuel-mechanical treatment on a large scale scarcely affects fire regime if applied under the current subsidies-investment schemes in the Mediterranean. The promotion of a bioeconomy focused on wood and timber products could contribute to make fuel-mechanical treatments at the landscape scale economically sustainable in the long-term (Fight et al., 2004). However, this will require of a paradigm shift in the economy of Mediterranean countries (where currently the market of wood and timber products is largely marginal). Nonetheless, the application of mechanical treatments can be much more suitable near urbanizations than PB, which entail negative impacts such as smoke or escaping risk. Grazing as a wildfire control tool is increasingly finding more supporters, since it decreases carbon emissions, while at the same time allows the recovery of some food products that override increasing water-demand systems dependent on intensive-production. However, other impacts associated to over-grazing pressure (soil compaction, herbaceous species selectivity, etc.), are associated with these practices. Most probably, a combination of different fuel management practices could lead to an optimal reduction of extreme wildfire events, increase ecosystem resilience, benefit local economies and preserve biodiversity under the threat that climate change supposes. Integrative strategies that take into account the various social, economic and ecological dimensions of fire regimes offer appropriate solutions for highly populated landscapes in a changing future.

5. Conclusions

Novel climates are increasingly expected to affect ecosystems during the 21st century: hot windy situations and hotter anticyclonic situations will arise and increase throughout the century. Novel climates can increase the potential of large wildfire events. PB plans have the capability to offset large wildfire events forecasted to the 21st century. By applying reasonable and feasible amounts (15,000 ha/year for all Catalonia), PB treatments can contribute to a great extent to the decrease high-intensity fires and to decrease extreme events. Their effectiveness is expected to increase if their application is adapted to ongoing fire activity. However, PB may also involve undesired effects on forest systems. We need to advance towards the recognition of fire as an intrinsic element of Mediterranean ecosystem dynamics. This recognition should facilitate a paradigm shift towards the development of adaptive fire management strategies focusing on the reduction of negative fire impacts rather than focusing on the total removal of this disturbance from the system. The fostering of strategies that combine multiple fuel management practices (such as grazing, mechanical treatments, etc.) will be the most suitable to integrate social, economic and ecological dimensions in building resilient landscapes and learning to coexist with fire. All these results provide useful information for governments interested in exploring the implementation of new fire policies under future climates.

Author contributions

AD and LB conceptualized the article. AD collected the data. AD, NA and LB developed the model. All authors analyzed the data. AD wrote the original draft, and all authors contributed to its review and editing.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.04.348.

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